

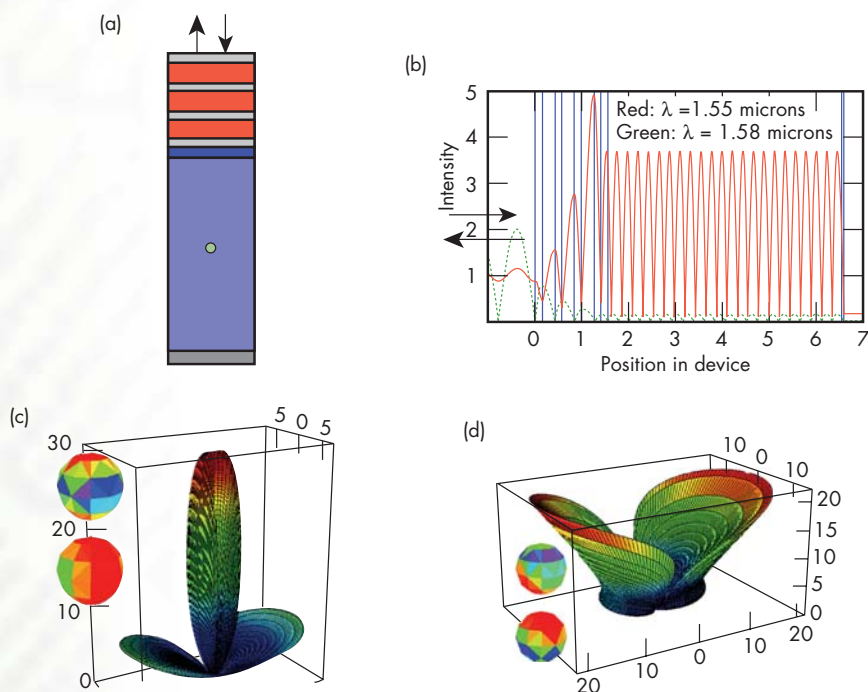
# Three-Dimensional Vectorial Time-Domain Computational Photonics



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**D**emand from customers with needs in secure data transmission, computer networking, and high-bandwidth instrumentation is pushing photonic integrated circuit (PIC) technology. Compact (LSI to VLSI), low-latency (sub-ps), wide-bandwidth (THz), ultrafast (100 Gb/s), miniaturized digital-logic, transmission, and sensor systems are potentially feasible.

Despite the strong photonic modeling capability at LLNL, new numerical methods are necessary as more complex photonic devices, materials, and configurations are devised. Three-dimensional time-domain design tools are fundamental to enabling and accelerating technologies for the realization of all-optical logic systems for data generation, transmission, manipulation, and detection.



**Figure 1.** Scattering in semiconductor Fabry-Perot interferometer. (a) The device: a metal-mirror-backed semiconductor cavity with a  $\lambda/4$  stack on top and a  $0.1\text{-}\mu\text{m}$ -radius scatterer; (b) the intensity of the electric field through the device on- and off-resonance (red and green traces, respectively); (c) and (d) the scattering pattern of the E field when the wavelength is, respectively, on- and off-resonance. In (d), the large central lobe is missing, and the maximum E field is reduced by 30 dB relative to the on-resonance case.

## Project Goals

We are filling the gap between existing modeling tools and those needed for Laboratory missions by extending the state of the art in simulation for the design of 3-D PICs. We have defined challenges that must be addressed in our codes, such as models for optical gain and nonlinearities, as well as microscopic, nonuniform, inhomogeneous structures.

## Relevance to LLNL Mission

The ability to model complex 3-D photonic devices in the time domain is essential to LLNL for a broad range of applications. These include: high-bandwidth instrumentation for NIF diagnostics; microsensors for weapon miniaturization within the DNT programs; encryption devices and circuits for secure communications for NAI surveillance applications; high density optical interconnects for high-performance computing (core of the ASCI mission); and the

Chemical and Biological National Security Program detection devices.

## FY2004 Accomplishments and Results

We have extended the Quench suite (a scalar 2-D narrow-bandwidth paraxial-propagation code used to model nonlinear optical devices) to model 3-D devices, and the EMSolve code (a vector 3-D broadband Maxwell's Equations solver used to model linear optical devices) to deal with carrier diffusion and time-varying material properties.

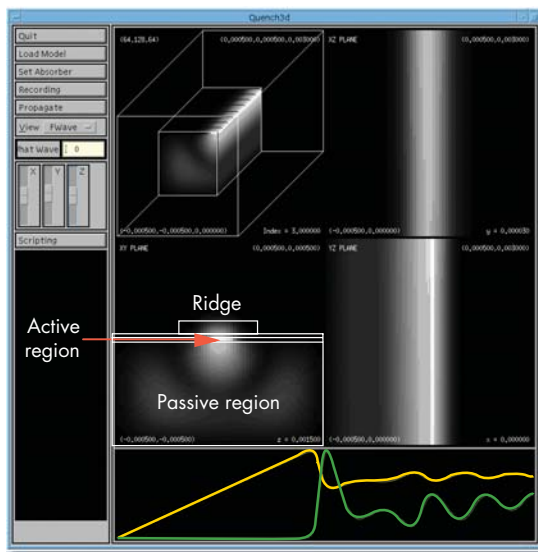
We have verified our nonlinear material models against literature results. We used our codes to model a steady-state off-bandgap Fabry-Perot interferometer with index perturbations (see Fig. 1). This was useful for the design of the next generation of ultrafast, highly sensitive radiation sensors for NIF x-ray diagnostics. Results provide quantitative information about the magnitude of the scattering to be expected

from a low-energy x ray hitting the sensor (both at and away from optical resonance), and showed the sensitivity of the device to the location of the x-ray absorption.

We coupled our 3-D carrier density decay-diffusion simulation to our bulk material models to generate complex refractive index distributions, which we then used in a 3-D BPM code to determine scattering from a carrier density distribution.

## Related References

1. Bond, T. C., and J. S. Kallman, "Time-Domain Tools for the Investigation of Gain-Quenched Laser Logic," *International Semiconductor Device Research Symposium*, Washington, D. C., December 2003.
2. Koning, J. M., D. A. White, R. N. Rieben, and M. L. Stowell, "EMSolve: A Three Dimensional Time Domain Electromagnetic Solver," *5th Biennial Tri-Lab Engineering Conference*, Albuquerque, New Mexico, October 2003.



**Figure 2.** Output of the Quench3D program modeling a short laser. Upper left: three planes that are viewed in the other parts of the main image (this shows we are looking at approximately the center of the device). Upper right: XZ plane. Lower left: XY plane. Overlaid on the lower left image is an illustration of the design of the laser being modeled. Lower right: YZ plane. The graph at the bottom shows the time history of the laser output (green line) and the average carrier density (yellow line).

## FY2005 Proposed Work

We will develop and incorporate gain and spontaneous emission algorithms into the EMSolve code and replace Quench3D's (see Fig. 2) scalar beam propagation solver with a vector finite-element beam propagation solver. The upgrade to EMSolve will allow us to model photonic crystal devices and semiconductor Fabry-Perot interferometers excited at the bandgap energy. The upgrade to Quench3D will allow us to examine the polarization dependence of the light emitted from semiconductor lasers. We will continue modeling devices for a variety of LLNL programs.